# Use of Hidden Variables in Modern Calculations of Angular Correlations of Gamma Quanta and Neutrons Emitted from Fission Fragments

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The hidden-variables (HV) theory was once put forward by opponents of the probabilistic interpretation of the wave function (EPR paradox). It was assumed that the state of the system could be predicted with a less uncertainty than this is admitted by the Heisenberg uncertainty principle, if one knew additional, that is HV. This theory is rejected by the community. However, examples can be given of how HV suddenly appear, for example, in modern simulations of the angular distributions of gamma quanta or neutrons emitted from fission fragments. This happens if one considers the spin of each fragment to have a definite direction in the plane perpendicular to the fission axis, and then averages over the directions of the spin in the azimuthal plane. In this way, the well-known phenomenon of the alignment of the spins of fragments in a plane perpendicular to the fission axis might be erroneously treated. Then the supposed direction of the fragment's spin appears as a HV. Contrary, in a consecutive quantum-mechanical approach, the state of the fragment is characterized by two quantum numbers: the spin and its projection onto the quantization axis *z*, which is along the fission axis. Then the alignment of the fragments merely means that the projection of their spins onto this axis is close to zero. And in the general case of incomplete alignment, it is necessary to use the density matrix.

Let us consider for illustration a simple two-level scheme of neutron decay. Let the initial nucleus in an excited state be characterized by the quantum numbers of an odd neutron: the orbital angular momentum $L$ and the total angular momentum $J = L + 1/2$. Suppose that by emitting a neutron, it transfers to the ground state of an even-even nucleus with $J = L = 0$. Then the neutron is emitted with the orbital angular momentum $L$. If $L = 0$, the neutron is emitted isotropically, and no question arises. Let us consider the variants with $L = 1$ and $L = 2$. In the HV model, the angular distribution of the emitted neutrons in the internal coordinate system will be $|Y_{LL}(\theta, \varphi)|^2 \sim \sin^2\theta$ and $\sin^4\theta$ in the cases of $L = 1$ and 2, respectively. After transformation to the angle $\vartheta$ relative to the fission axis $z$ in the laboratory system and averaging over the azimuthal angle $\phi$ of the spin in the $(x,y)$ plane, one arrives at the angular distributions in the labsystem, calculated within the HV-theory: $\Psi_{\text{h.v.}}(\vartheta) = 1 + \cos^2\vartheta$ if $L = 1$, and $\Psi_{\text{h.v.}}(\vartheta) = 1 + \frac{2}{3}\cos^2\vartheta + \cos^4\vartheta$ if $L = 2$. Contrary, within the framework of the quantum-mechanical approach one obtains $\Phi(\vartheta) = |Y_{10}(\vartheta,\varphi)|^2 \sim \cos^2\vartheta$ at $L = 1$, and $\Phi(\vartheta) = |Y_{20}(\vartheta,\varphi)|^2 \sim 1 - \frac{2}{3}\cos^2\vartheta + \frac{1}{9}\cos^4\vartheta$ at $L = 2$. The difference speaks for itself.

Among the other examples of use of HV, I point out the use of the immeasurable parameter $\xi$ in the method of specific differences for the elimination of the Bohr—Weisskopf effect in the study of the hyperfine splitting in heavy ions of $^{209}$Bi [1]. In [2], the angular distribution of conversion muons from fragments of prompt fission was calculated within the framework of the quantum-mechanical approach. The monograph [3] also considers the emission of "prompt" muons, which are analogous to prompt – that is, scission neutrons.

1. L. V. Skripnikov, S. Schmidt, J. Ullmann *et al.* Phys. Rev. Lett. **120**, 093001 (2018).
2. F. F. Karpeshin. Yad. Fiz. **40**, 643 (1984) [Sov. J. Nucl. Phys. **40**, 412 (1984)].
3. F. F. Karpeshin. Prompt Nuclear Fission in Muonic Atoms and Resonance Conversion, Saint Petersburg: "Nauka", 2006.